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Published in:
Journal of Modern Power Systems and Clean Energy

Link to article, DOI:
10.1007/s40565-016-0246-z

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

J. Mod. Power Syst. Clean Energy
DOI 10.1007/s40565-016-0246-z

Value assessment of hydrogen-based electrical energy storage in view of electricity spot market

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Abstract Hydrogen as an energy carrier represents one of the most promising carbon-free energy solutions. The ongoing development of power-to-gas (PtG) technologies that supports large-scale utilization of hydrogen is therefore expected to support hydrogen economy with a final breakthrough. In this paper, the economic performance of a MW-sized hydrogen system, i.e. a composition of water electrolysis, hydrogen storage, and fuel cell combined heat and power plant (FCCHP), is assessed as an example of hydrogen-based bidirectional electrical energy storage (EES). The analysis is conducted in view of the Danish electricity spot market that has high price volatility due to its high share of wind power. An economic dispatch model is developed as a mixed-integer programming (MIP) problem to support the estimation of variable cost of such a system taking into account a good granularity of the technical details. Based on a projected technology improvement by 2020, sensitivity analysis is conducted to illustrate how much the hydrogen-based EES is sensitive to variations of the hydrogen price and the capacity of hydrogen storage.

Keywords Electrical energy storage (EES), Electricity spot market, Fuel cell combined heat and power plant (FCCHP), Hydrogen, Hydrogen storage, Mixed-integer programming (MIP)

Crosscheck date: 26 September 2016

Received: 24 June 2016 / Accepted: 27 September 2016

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1 Introduction

The growing need of sustainable energy systems calls for new forms of energy carriers. Although many alternative sustainable energy pathways have been proposed, the so-called "hydrogen economy" has received particular attention in the past decade [1–3]. As depicted in Fig. 1, in hydrogen economy, hydrogen is utilized as a viable and advantageous energy carrier option for storing and delivering clean and efficient energy in a wide range of applications. Another focus of hydrogen economy is on creating the synergies between different energy systems by developing a hydrogen-enabled integrated energy system solution. With this solution, the flexibility of each energy system can be utilized in an optimal and synthetic manner [4]. The challenges faced by each energy system, such as integrating intermittent renewables into the electrical grid, can therefore be addressed properly from an integrated perspective.

Earlier investigations on hydrogen economy primarily focus on how to realize, improve and take advantage of the bidirectional conversion feature between electricity and hydrogen, as depicted in the shaded area of Fig. 1. With technologies that are available today, this closed loop

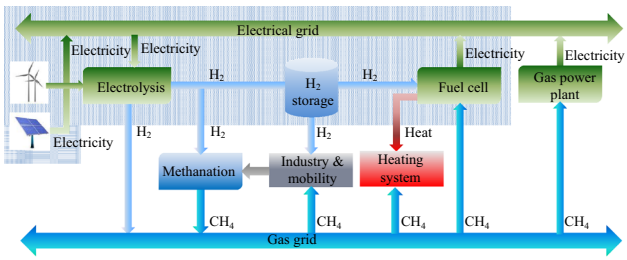

Fig. 1 Schematic overview of the role of hydrogen systems in a multi-carrier energy system

operation converts electricity into hydrogen by electrolysis, and re-electrifies the hydrogen using various fuel cell technologies. The round trip efficiency today is as low as 30% to 40% [5], disregarding the possibility of cogeneration if heat produced during the process, such as by fuel cells, can be captured for use. Despite this low efficiency, the interest of using this kind of hydrogen energy storage alternative keeps growing. The first full-scale hydrogen-powered community of EU demonstrated in Lolland, Denmark presents a showcase example of this hydrogen-based solution [6]. In this application, excess wind power is converted to hydrogen via centralized production and stored in low pressure tanks. Through a number of installations of domestic fuel cell (FC) micro-combined heat and power systems (micro-CHPs), the need for heat and electricity from each household is met individually, resulting in 100% carbon neutral. Other applications for utilizing this kind of hydrogen solution to facilitate renewable integration can also be found in [7, 8]. The installed capacity of these real-life applications are typically below 100 kW.

Recent investigations on hydrogen economy extend the earlier development by enabling a much larger scale application for hydrogen-based energy storage, i.e. so called power-to-gas (PtG). As illustrated in the unshaded area of Fig. 1, hydrogen produced by electrolysis can be accommodated directly in the gas grid, converted into methane, or utilized in the industrial and mobility sectors. Although the amount of hydrogen that can be added to natural gas in the gas grid strongly depends on the composition of the natural gas at the point of injection, the total storage potential is huge. For instance, the potential storage capacity for Dutch gas grid is estimated around 0.83 TWh, assuming hydrogen is stored in a 0.5% mixture with methane in the current gas infrastructure [9]. Another advantage of PtG is by utilizing the existing gas infrastructure to transfer energy at a large volume over a large distance, the investment on electrical infrastructure might be mitigated. However, due to the economic and environmental concerns for PtG, the present technology might be more suitable for countries with an extensive gas infrastructure, and which are lacking the characteristics required for other kinds of large scale storage applications such as pumped hydro and compressed air [10].

To better understand the techno-economic performance of hydrogen economy, a number of investigations have been performed in [11–16], wherein the focus has been given to both individual transformation process and integrated system solutions like hydrogen storage together with renewables. Although these studies provide application-based analysis and the results are indicative, few of them consider the impacts of energy price volatility. In an energy system with high share of renewables, the energy price, especially the electricity spot price, can be dramatically affected by the production from renewables such as wind [17, 18], which may to a great extent affects the operational economy of different hydrogen-based applications. For countries like Denmark that aims for 100% renewable with 50% electricity produced by wind [19], such kind of analysis must consider the energy price volatility.

The study carried in this paper, as part of a demo-oriented feasibility analysis "CopenHydrogen" [20], presents an economic dispatch based generic mathematical model for facilitating the assessment of the operational economy of hydrogen systems that can function as a bidirectional electrical energy storage (EES) in view of a multi-energy market environment. Compared to studies conducted in the existing literature that also orient at analyzing the techno-economic performance of hydrogen systems, the major contributions of this work include: ① modeling the dynamic transitions among various operation states (i.e. on/off/standby) for different energy conversion technologies (i.e. electrolysis and fuel-cell combined heat and power unit) in a hydrogen system; ② presenting a generic mathematical model of the hydrogen system that allows for flexible setup with varying technical parameters and economic factors from a multi-energy perspective as well as easy extension (e.g. including different types and multiple numbers of electrolysis); ③ conducting a techno-economic analysis with informative results based on the up-to-date market data collected from Nordpool spot (i.e. a power market with the highest amount of wind power) and a qualified guess of the hydrogen system′s technical performance by 2020.

In Section 2, the developed economic dispatch model is described in detail. Section 3 provides an overview of data applied to this study, i.e. the technical parameters of the simulated CopenHydrogen system and the energy prices in Denmark. Simulation-based case studies are presented in Section 4, which not only illustrate the effectiveness of the developed model-based approach but also show how sensitive the economic performance of such a hydrogen-based EES is to factors such as hydrogen selling price and the size of hydrogen storage. Discussion and conclusion are given in Section 5.

2 System description and mathematical modelling

2.1 System description

In the "CopenHydrogen" system, hydrogen-related technologies are carefully investigated according to both the cost-effectiveness and the technology matureness level. Currently, Alkaline water electrolysis (AWE) is considered as the least costly technologies with the highest technology maturity among different water electrolysis solutions [21], and can be sized at MW scale by easily combining a number of hundred kW modules. Because hydrogen produced by an AWE is typically less than 40 bar, it is necessary to equip an external compressor to increase the volumetric energy density of the produced hydrogen at around 700 bar. This makes it more efficient to store and handle hydrogen at large scale. With respect to the FC-based CHP applications, proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cells (PAFC), and solid oxide fuel cell (SOFC) are popular technologies used for large-scale combined heat and power applications with different cost-effectiveness and operational features [22–26]. A short comparison of different FCCHP technologies is given in Table 1. It is worth to note that the part-load efficiency of FCCHPs is generally high and the labels given in the table are only for comparison. For example, for SOFC-based CHP applications the normalized electrical efficiency can be up to 80% at 50% load. With respect to start-up time, a cold start-up for a PEMFC can be as short as several minutes, and for a SOFC this can be up to tens of hours.

The resulted "CopenHydrogen" system as illustrated in Fig. 2 is comprised of an AWE for hydrogen production, a hydrogen tank for storing compressed hydrogen, and a PEM-based FCCHP plant for producing heat and electricity. It is assumed that there exist the corresponding energy carrier infrastructures that can support the energy exchange between the hydrogen system and other energy systems. Correspondingly, the exchanged energy can be traded in three marketplaces, i.e. electricity spot market, heat market and hydrogen market. Although the oxygen produced through electrolysis as a side product may also generate an additional value stream for the hydrogen system, it is assumed the oxygen product is not traded due to the lack of evidence proving the viability.

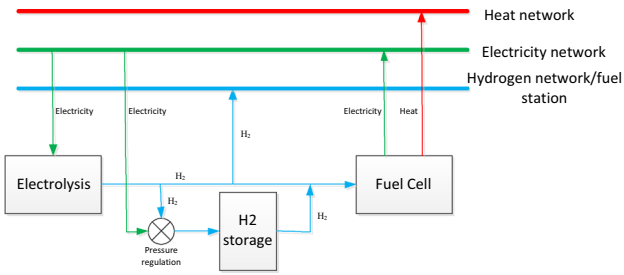

Fig. 2 Energy exchange diagram between the modeled hydrogen system and the related energy infrastructure

2.2 Mathematical model of economic dispatch: objective

The economic dispatch often solves a short-term unit commitment problem together with the optimal scheduling with a fixed time resolution, i.e. usually on an hourly time resolution, under a large set of unit and system constraints. The solution of the economic dispatch provides the commitment status and dispatch scheduling for units during the respective scheduling period under study [27], which offers an ideal path to assess the market-based operational economy, i.e. the variable cost (VC), of an energy system. Although there exist a large number of economic dispatch and unit commitment models developed for power system applications [28], few has been developed for the investigated hydrogen system.

In this study, the economic dispatch of the hydrogen system is modeled as a mixed integer programming (MIP) problem in GAMS [29]. The objective is to minimize the total VC of the three subsystems for one optimization period with T time intervals as in (1).

$$\min \sum_{t=1}^{T} \sum_{j \in J} \left\{ C_{j,t}^{op} + C_{j,t}^{su} \right\} \tag{1}$$

where T,t are the set and index of time slots; $J = \{EL, HS, FC\}$ and j are the set and index of three subsystems, i.e. AWE, hydrogen storage and FCCHP respectively. The cost variable is a sum of the start-up cost $C_{j,t}^{su}$ of subsystem j at

Table 1 A short comparison of FCCHP solutions (sub-MW class)

FCCHP	Electrical efficiency (%)*	CHP efficiency (%)	Start-up time	Part-load performance
PEMFC	23–40	65–90	Fast	Medium
PAFC	35–45	85–90	Medium	High
SOFC	30–60	67–90	Slow	Low

Note: * The efficiency is reported according to higher heating value (HHV)

t and the running cost $C_{j,t}^{op}$ as in (2). The running cost is dependent on the energy price $\lambda_{k,t}$ and the amount of energy consumed in form k and produced in form k^* (an alias of k), during the time interval Δt. $K = \{el, h_2, th\}$ and k are the set and index of three energy forms, i.e. electricity, hydrogen and heat. $P_{j,k,t}^{in}$ and $P_{j,k*,t}^{out}$ represent the instant power consumed in the form k and produced in the form k^* respectively.

$$C_{j,t}^{op} = \sum_{k \in K} (\lambda_{k,t} \cdot P_{j,k,t}^{in} - \lambda_{k*,t} \cdot P_{j,k*,t}^{out}) \cdot \Delta t \tag{2}$$

The objective is subject to a number of constraints that represent the system dynamics. To achieve a relatively generic representation, these constraints are grouped into two categories, namely energy conversion and energy storage, which are explained in the following sub-sections.

2.3 Constraint group A: energy conversion

The modeled group A constraints, as in (3)–(19), represent the process of energy conversion for both the AWE and the FCCHP.

$$w_{j,t}^{on} + w_{j,t}^{st} + w_{j,t}^{off} = 1 \tag{3}$$

$$w_{j,t}^{st} \le 1 - w_{j,t-1}^{off} \tag{4}$$

$$w_{j,t}^{st} \ge w_{j,t-1}^{off} - 1 \tag{5}$$

$$w_{j,t}^{off} \le 1 - w_{j,t-1}^{st} \tag{6}$$

$$w_{j,t}^{off} \ge w_{j,t-1}^{st} - 1 \tag{7}$$

$$U_{j,t}^{cs} \le \frac{1 - w_{j,t}^{off} + w_{j,t-1}^{off}}{2} \tag{8}$$

$$U_{j,t}^{cs} \ge w_{j,t-1}^{off} - w_{j,t}^{off} \tag{9}$$

$$U_{j,t}^{ws} \le \frac{1 - w_{j,t}^{st} + w_{j,t-1}^{st}}{2} \tag{10}$$

$$U_{j,t}^{ws} \ge w_{j,t-1}^{st} - w_{j,t}^{st} \tag{11}$$

$$C_{j,t}^{su} = \lambda_{k,t} \cdot \left(U_{j,t}^{ws} \cdot C_j^{ws} + U_{j,t}^{cs} \cdot C_j^{cs} \right) \tag{12}$$

$$w_{j,t}^{on} = \sum_{n=1}^{N} s_{j,k,t}^{n} \tag{13}$$

$$s_{j,k,t}^{n} \cdot \underline{P_{j,k}^{n}} \le P_{j,k,t}^{on,n} < s_{j,k,t}^{n} \cdot \overline{P_{j,k}^{n}}, \quad \forall n = \{1, \ldots, N-1\} \tag{14}$$

$$s_{j,k,t}^{N-1} \cdot \underline{P_{j,k}^{N}} \le P_{j,k,t}^{on,N} \le s_{j,k,t}^{n} \cdot \overline{P_{j,k}^{N}} \tag{15}$$

$$P_{j,k,t}^{on} = \sum_{n=1}^{N} s_{j,k,t}^{n} \cdot P_{j,k,t}^{on,n} \tag{16}$$

$$P_{j,k^*,t}^{out} = \sum_{n=1}^{N} s_{j,k^*,t}^{n} \cdot \eta_{j,k^*}^{n} \cdot P_{j,k,t}^{on,n} \tag{17}$$

$$P_{j,k,t}^{st} = w_{j,t}^{st} \cdot Q_{j,k}^{st} \tag{18}$$

$$P_{j,k,t}^{in} = P_{j,k,t}^{on} + P_{j,k,t}^{st} \tag{19}$$

where (3)–(7) model the dynamic transition among three operation states, i.e. on/off/standby which are indicated by the binary variables $w_{j,t}^{on}$, $w_{j,t}^{off}$ and $w_{j,t}^{st}$ respectively. (8)–(9) and (10)–(11) model two dynamic start-up processes, i.e. the cold start-up (from off to on) indicated by the binary variable $U_{j,t}^{cs}$ and the warm start-up (from standby to on) indicated by the binary variable $U_{j,t}^{ws}$. The start-up cost at t is represented by $C_{j,t}^{su}$ and expressed in (12) as a sum of the start-up cost of either a cold start C_j^{cs} or a warm start-up C_j^{ws} which are two cost parameters measured as energy consumption in form k. Typically, the manufacturers use data collected from experiments to describe the conversion rate between two energy forms at different load conditions, the resulted format is therefore either a curve or a table. In this paper, we assume the entire operational regime for a subsystem j is divided into a total number of N part-load operational regimes, as indicated by (13). Each operational regime is assumed to have a fixed conversion rate. This would allow us to easily adapt the experimental information into a mathematical model. The binary variable $s_{j,k,t}^{n}$ denotes which operational regime (also in the corresponding energy form k) is selected if the system is on. This implies, if the system is at on state, i.e. $w_{j,t}^{on}$ equals one, only one operational regime can be selected. If $w_{j,t}^{on}$ equals zero, no operational regime will be selected. If we assume a FCCHP has two operational regimes, this means the FCCHP will have a low efficiency regime and a high efficiency regime. Correspondingly, each regime would have a fixed energy conversation rate for hydrogen to heat and one for hydrogen to electricity. The continuity between two neighboring operational regimes is modeled by (14) and (15), wherein the power consumption that falls into the nth operational regime at time t is indicated by $P_{j,k,t}^{on,n}$. The power consumption for subsystem j in energy form k at time t is $P_{j,k,t}^{on}$ which is therefore the sum of the power consumed in all operational regimes as in (16). Equation (17) models the energy conversion from the energy source in form k to the energy product in form k^* (an alias of k) at the corresponding part-load conversion rate η_{j,k^*}^{n}, if

subsystem works at the nth operational regime. The energy consumption at standby mode is modeled in (18), assuming the power consumption during standby is a constant parameter $Q^{st}_{j,k}$. Equation (19) sums up the power consumption at both on and standby modes.

A state transition diagram between two consecutive time slots is given in Fig. 3 to further illustrate the dynamic constraints (4)–(11). The black-arrow lines represent the feasible transitions, the blue-arrow line and the red-arrow line represent the cold start-up and warm start-up respectively. In principle, it is possible that an AWE/FCCHP could also make a transition from off to standby or vice versa, as illustrated by the dotted arrow lines, which can be understood as a cold start or shutdown from standby. However, considering a cold start-up time for a state-of-the-art AWE/FCCHP can be relatively short when the optimization is performed on hourly scale, it would be very impractical to cold start the system towards standby or to move from standby to off. These infeasibilities are modeled in (4)–(7).

2.4 Constraint group B: energy storage

The mathematical formulation of a high pressure hydrogen tank is expressed as in (20)–(24), using the generic index.

$$\underline{Q_{j,k}} \le Q_{j,k,t} \le \overline{Q_{j,k}} \tag{20}$$

$$Q_{j,k,t} = Q_{j,k,t-1} + P^{in}_{j,k,t} \cdot \Delta t - P^{out}_{j,k,t} \cdot \Delta t \tag{21}$$

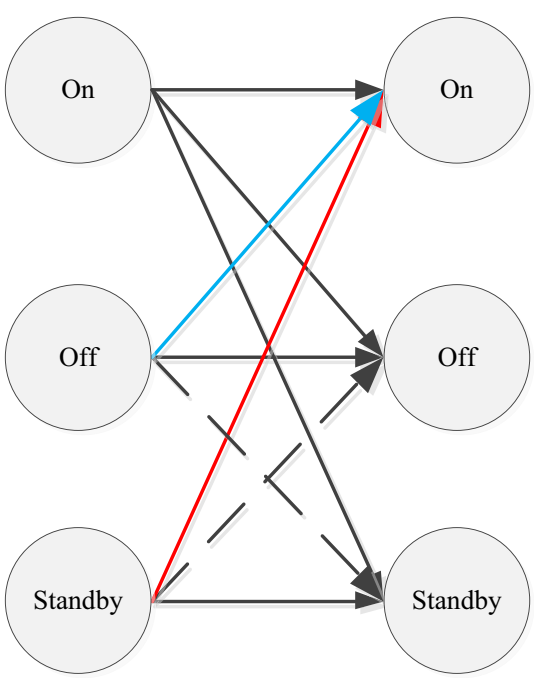

Fig. 3 State transition diagram for the modeled hydrogen system

$$\underline{P^{in}_{j,k}} \le P^{in}_{j,k,t} \le \overline{P^{in}_{j,k}} \tag{22}$$

$$\underline{P^{out}_{j,k}} \le P^{out}_{j,k,t} \le \overline{P^{out}_{j,k}} \tag{23}$$

$$P^{in}_{j,k,t} = P_{j,k^*,t} \cdot \eta_{j,k} \tag{24}$$

where (20) describes the storage capacity limit of the hydrogen storage and (21) models the recurrence relation of the hydrogen gauge $Q_{j,k,t}$ between two consecutive time intervals. The flow rate of hydrogen w.r.t. compression $P^{in}_{j,k,t}$ and release $P^{out}_{j,k,t}$ are modeled in (22) and (23) respectively. Equation (24) models the compression process during which electricity $P_{j,k^*,t}$ is consumed to produce high pressure hydrogen $P^{in}_{j,k,t}$ at the efficiency $\eta_{j,k}$. Because self-discharge and standby losses for high pressure hydrogen tanks are generally negligible, the two factors are not considered in this study. However, they can be easily included as cost parameters or variables if the corresponding information is available.

3 Data applied

Data applied in this study consists of two parts: technical-economic parameters for the hydrogen system as given in Table 2, and the energy market prices for different energy products.

3.1 Parameters for the hydrogen system

With respect to the parameters used for simulating the variable operation of the hydrogen system as well as its economy, the economy table created for Copenhydrogen [30] is used to present a qualified guess for 2020, wherein the capital expenditure (CAPEX) and fixed operation & maintenance cost (FO&M) are used to calculate the payback time for the hydrogen project. The technical parameters are also based on a projected technology improvement by 2020, and represent a mix of experimental data and data quoted from several technology manufacturers such as GreenHydrogen, ITM Power for AWE and Ballard for PEMFC [20]. Efficiency data or the conversion rate is provided according to HHV. For the FCCHP that produces both electricity and heat, its capacity and related cost items are expressed in the form of electricity. In addition, each operation regime of the FCCHP includes two conversion rates: one for electricity production (upper value given in the cell) and one for heat production (lower value given in the cell).

In principle, such a MW-scale system is able to produce 28 kg hydrogen maximally on an hourly basis. The hydrogen storage therefore is sized to store all the produced hydrogen for up to 10 hours. To ensure there is enough

Table 2 Parameters of the hydrogen system

	AWE	PEM-based FCCHP	Hydrogen storage
$\left\{\underline{P^{in}_{j,k}}, \overline{P^{in}_{j,k}}\right\}$	100–1000 kW	100–1000 kW	0–28 kg/hour
$\left\{\underline{P^{out}_{j,k}}, \overline{P^{out}_{j,k}}\right\}$	–	–	0–70 kg/hour
$\left\{\underline{Q_{j,k}}, \overline{Q_{j,k}}\right\}$	–	–	0–280 kg
$\eta^1_{j,k}$	0.011 kg/kWh	11.3 kWh/kg 12.6 kWh/kg	0.45 kg/kWh
$\eta^2_{j,k}$	0.019 kg/kWh	14.3 kWh/kg 15.1 kWh/kg	0.45 kg/kWh
$\eta^3_{j,k}$	0.028 kg/ kWh	13.7 kWh/kg 21.5 kWh/kg	
C^{ws}_j	10 kWh	10 kWh	
C^{cs}_j	100 kWh	100 kWh	
$Q^{st}_{j,k}$	1 kW	1 kW	
CAPEX*	370 €/kW	1900 €/kW	105 €/kg
FO&M	2% CAPX/year	2% CAPX/year	2% CAPX/year

Note: * 1 € = 7.5 DKK

hydrogen to power the PEM-based FCCHP plant, a maximum release rate 70 kg per hour is set for the hydrogen storage. As in Table 2, for AWE and FCCHP, three operational regimes are considered, i.e. 10%–30% load, 30%–70% load and 70%–100% load, assuming there is a fixed rate of energy conversion in each regime.

3.2 Energy prices for Denmark

Today, except for the electricity that can be traded in the Nordic electricity spot market in Denmark, both heat and hydrogen are either traded over the counter or regulated by individual authorities. In this study, only the variability of electricity of DK-east is considered. As for the prices of the other energy forms, the price for heat is set as 63.5 €/MWh [31] which reflects the district heating price (without tax and other fees) for Copenhagen in 2015. The price for hydrogen is set as zero for a baseline scenario in the later conducted analysis, assuming there is no market and infrastructure supporting PtG.

The spot price of electricity in Denmark has shown a high volatility due to the high penetration of wind power which was recorded as 42 percent of the Danes'™ electricity consumption in 2015. In this study, the 2015 data for DK-East where Copenhagen is located is downloaded from Energinet.dk [32]. An overview of the electricity spot price and wind power penetration in DK-East is given in Fig. 4. As illustrated by the histograms in Fig. 4a and Fig. 4b, both hourly electricity spot price and hourly wind power penetration (i.e. the fraction of energy produced by wind compared with the total generation) have shown a large degree of volatility. As for the wind power penetration, it

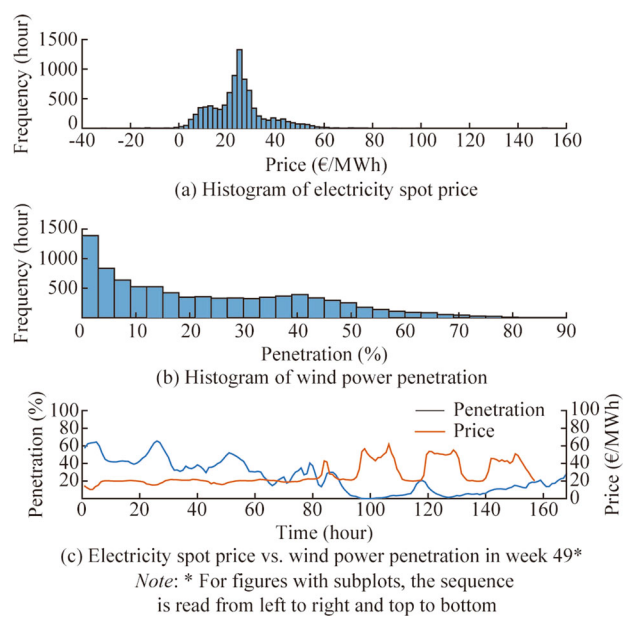

Fig. 4 An overview of hourly electricity spot price and wind power penetration for DK-East 2015

varies between almost 0% and 90% over the year with an average level around 23%. W.r.t the electricity spot price, the highest and the lowest values reach 150 €/MWh and −31.4 €/MWh respectively and the average is 24.5 €/MWh. A closer look at the correlation between wind power penetration and electricity spot price is shown in Fig. 4c using week 49 as an example, where it can be clearly observed for hours with low wind production the electricity price can be high.

4 Simulation and results

In this section, a baseline scenario is first presented based on data given in Section 3. The simulated horizon is one year with an hourly resolution, assuming the energy price is known. Such assumption implies the best operational economy that could be achieved for the studied system. A sensitivity analysis is further conducted, which illustrates how the hydrogen selling price and the capacity of hydrogen storage would affect the overall economic performance.

4.1 Baseline scenario

An overview of the system performance in week 49 of 2015 is given in Fig. 5 as a snapshot taken from the annual performance picture. Given the energy prices illustrated as in Fig. 5a, the system injects heat to the heating system and exchange electricity with the electrical grid as shown in Fig. 5b. The hydrogen flow is presented in Fig. 5c, which also indicates the working condition for the AWE and the FCCHP respectively. For the AWE, it always intends to work at the high-load operational regime when electricity price is low in order to produce hydrogen. This is due to the assumption that the produced hydrogen is not tradable unless it is used to fuel the FCCHP for electricity and heat production. W.r.t. the FCCHP, it generally operates at the second operational regime with high electrical efficiency when the electricity price is high. Because the hydrogen storage offers additional flexibility to the system, this allows the FCCHP to use the stored hydrogen to produce high amount of heat when the electricity prices are low but can still be economically profitable. Figure 5d shows the variation of state of charge (SOC) of the hydrogen storage.

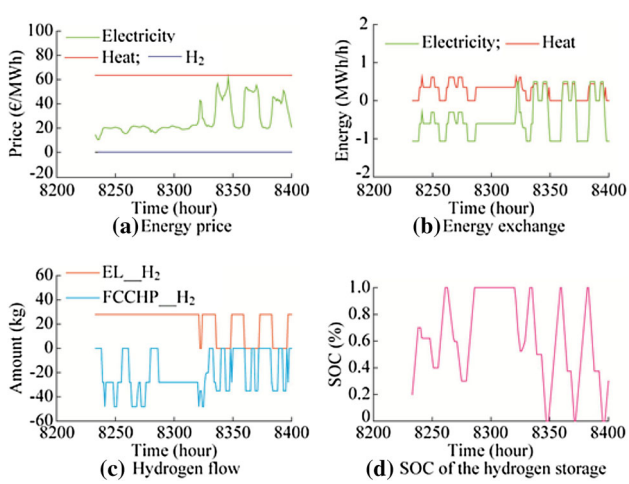

Fig. 5 An overview of the system performance in week 49 of 2015

An overview of the simulated annual performance is given in Table 3 and in Fig. 6. From the annual perspective, although the system is able to generate approximately 88,000 € per year, the resulted payback time (PT) is still extremely long, i.e. 54.8 years when the discount rate is zero and the annual income remains the same in the project period. During the simulated period, both the AWE and the FCCHP have not been turned off due to the large difference between the two start-up modes and the power consumption at the standby mode is very little. In terms of the monthly performance, it can be easily observed that the highest amount of income (the reverse of VC) is achieved in the seventh month when the averaged electricity price is the lowest. Correspondingly, the lowest amount of income is achieved in the second month when the averaged electricity price reaches the highest over the year.

4.2 Sensitivity analysis

The economic performance of such a hydrogen-based EES system can be easily affected by many factors. In this section, Fig. 7 illustrates how the variation of hydrogen storage capacity and the variation of the hydrogen selling price can affect the economic performance in Fig. 7a and Fig. 7b respectively.

In Fig. 7a, results achieved from the baseline scenario in terms of the annual income and the value for the hydrogen storage capacity are used as reference. It can be easily observed that the annual income increases as the capacity increases, implying a larger hydrogen storage brings in more variable income when the selling price of hydrogen is zero. However, this relatively small amount of annual income increase is not large enough to reduce the payback time down to a feasible value. Although an optimal solution found when the storage is sized as three times large of the reference value can reduce the payback time by 4.3%, the resulted payback time is still as long as 52.4 years. In Fig. 7b, a new reference case is selected in order to give better illustration of the sensitivity analysis. For the reference case, the hydrogen price is set as 7.5 €/kg and the resulted payback time is only 1.49 years. Comparing to the results achieved from the baseline scenario, this reduces the payback time by more than 97%. The reason for achieving such a very optimistic value is mainly because the high efficiency and the low CAPEX of the AWE can turn hydrogen production into a profitable business. This also means there is no need to operate the FCCHP anymore, and the hydrogen storage could be considered as unnecessary if the produced hydrogen can be directly injected into the hydrogen infrastructure such as gas networks or hydrogen distribution systems. The reduced use of the FCCHP can also be observed when the hydrogen price drops. For instance, when the selling price of hydrogen is 20% of the

Table 3 Annual performance of the studied hydrogen system

Performance parameters	AWE	PEM-based FCCHP	Hydrogen storage
On (hours)	7679.0	6461.0	–
Standby (hours)	1081.0	2299.0	–
Electricity (MWh)	−7661.5*	3050.9	−135.4
Heat (MWh)	–	2697.5	–
Hydrogen(ton)	214.4	−214.4	–
VC (€/year)	−87,928.1		
PT(year)	54.8		

Note: * A negative value indicates the energy is consumed

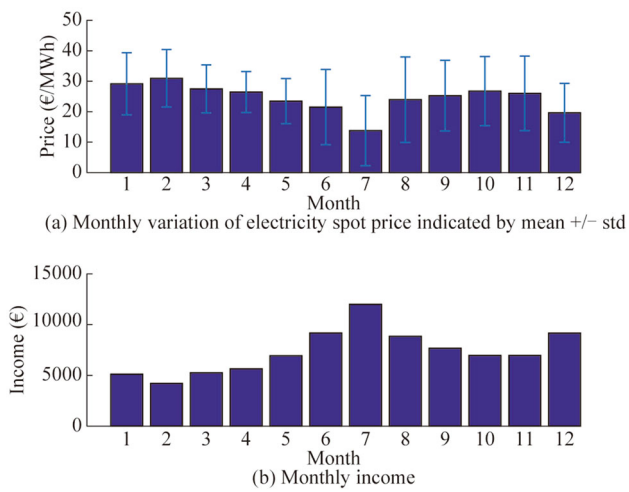

Fig. 6 An overview of monthly performance of the system

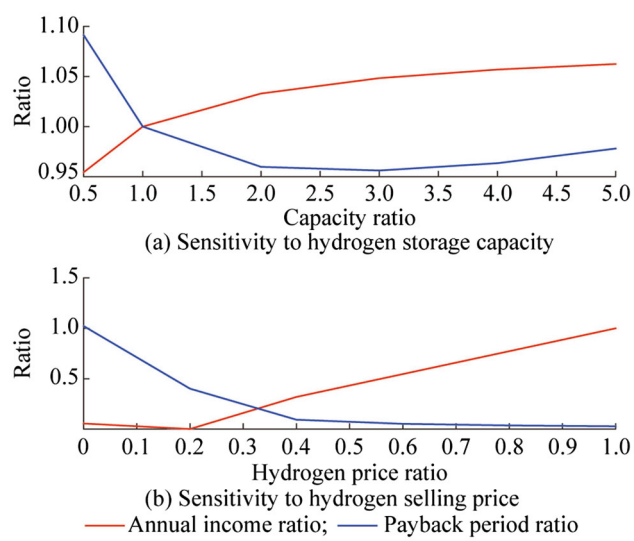

Fig. 7 Economic sensitivity analysis of the hydrogen EES

reference value, the total number of hours for the FCCHP working at on status is already reduced to 236, resulting in a payback time of 21.5 years.

5 Discussion and conclusion

This paper presented a relatively generic economic dispatch model for the hydrogen-based EES system that constitutes different hydrogen technologies, namely AWE, FCCHP and hydrogen storage. The developed MIP model includes key operational features of the hydrogen system, can therefore be easily used to support different kinds of investigations such as economic feasibility analysis, optimal scheduling and online/offline dispatch etc. In this paper, it is used to conduct a project-based feasibility analysis for the so-called Copenhydrogen project which aims to develop a MW-scale hydrogen-based EES solution. Projected technology data by 2020 is applied to the analysis in the context that different energy price setups for different energy products coexist. The electricity prices applied are quoted from the Danish power system in 2015 when a new record of wind power penetration was reached. It therefore gives a good representation of the future electricity price, in terms of value and volatility, for the Danish energy system that aims for 50% wind power by 2020.

From the case-based analysis, when assuming there is no market price for the produced hydrogen, there is hardly any economic feasibility for such a hydrogen-based EES system. However, it was clearly observed from the monthly overview that for periods with low averaged electricity price and large price variation, the profitability of such an EES can be relatively higher than the other periods. For a future power system with more wind power, these low price moments might be observed more frequently than the current situation, implying a shorter payback time of such system can be expected. The increase of hydrogen storage capacity could also increase the profitability of this system; however this increase is limited by the low round-trip electrical efficiency of the system, the fixed heat price and

the prohibited selling of hydrogen. This economic unviability is easily broken when the hydrogen can be traded on a regular basis, assuming there exits both a hydrogen market with high liquidity and a hydrogen infrastructure allowing for hydrogen storage and transportation. Since both the two key factors are currently not widely available, the level of economic viability for such a hydrogen-based ESS in practice could be much lower than the simulated best-case analysis. However, the results verify that using electrolysis to produce hydrogen can be considered as a reliable profitable solution. This is much in line with several existing studies, such as [33]–[34], which explain the applicability of hybrid wind/hydrogen solutions.

Comparing to the other storage technologies that can also take advantage of performing energy arbitrage in a electricity spot market, the study performed in [35] showed that compressed air energy storage (CAES) and pumped hydro were the two winners. The comparison was performed based on a unified size of 300 MWh scale energy storage with a discharge rate of 50 MW, while using annualized cost for producing the energy output from the storage system as the metric: electricity fed back onto the grid during peak hours and, in the case of producing excess hydrogen for vehicles, hydrogen. The economy of hydrogen storage was considered as close to technologies like Redox flow batteries and was worse than NaS. However, because life-time economic comparison performed in [35] was based on a numerical estimation rather than an optimization-based analysis, moreover, since the variation of technical parameters and the economic variables could easily affect the results, making an up-to-date comparison would be worthwhile.

Using hydrogen-based solutions to provide ancillary services for power system operation, such as frequency control and power balancing etc., would offer another promising value stream to hydrogen technology developers. This is due to the fact that the pay of ancillary service is often much higher and more reliable than what can be achieved from an electricity spot market-based energy arbitrage operation. As a trade-off, a number of design and operational factors (e.g. response time, ramp rate, controllability etc.) of hydrogen-based technologies have to be carefully investigated to ensure their compliance to the technical requirements of different ancillary services. Further, as an alternative hydrogen-based large scale EES solution to the modeled system, the technology portfolio of PtG, which includes gas network, blending process, gas distribution and gas power plant also needs dedicated research focus from both technological and business perspective. Applying the developed economic dispatch model to these research subjects with appropriate extensions is among the prioritized future work.

Acknowledgment The authors thank the financial support of Innovation Fund Denmark through Project 3045-00012B.

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